National Aeronautics and Space Administration

Gravitational Wave Astronomy – Opening New Windows

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Program: Strategic

Project Objective:

This Initiative supports research in **gravitational-wave detection** at **low frequencies** (0.01 to 100 mHz) with the planned space-based mission **LISA**, and at **very low frequencies** (0.1 to 10 nHz) by monitoring the regular radio emission of an **array of millisecond pulsars**.

Specifically, for **LISA**:

- We supported the new **LISA Data Challenges** (bit.ly/lisa-ldc), and outlined the requirements and design of the LISA science ground segment.
- We investigated high-throughput **deep-learning techniques** for GW data analysis—see FY18/19 results to the side [5,6,7].
- We worked on a **fundamental theoretical problem** in LISA data analysis—the simultaneous detection and characterization of thousands of superimposed signals, focusing on the **near-degeneracy** and potential **confusion** of extreme-mass-ratio inspiral sources.

For the north-American pulsar-timing-array consortium **NANOGrav**:

- We continued **high-profile theory and data-analysis activities** [1,2,3,4] such the search for stochastic GW backgrounds in NANOGrav's newest dataset, the Bayesian modeling of pulsar noise and interstellar medium effects, the astrophysical interpretation of GW limits, and the robust treatment of ephemeris uncertainties.
- Using Palomar, we searched for **electro-magnetic signatures of supermassive black-hole binaries** by monitoring of AGNs with velocity offset broad lines.

Benefits to NASA and JPL:

The direct detection of gravitational waves by LIGO, announced in February 2016, opened a **new window on the Universe**. In addition to participating in LIGO, JPL scientists and engineers have played key roles in developing technologies and analysis techniques to explore the GW spectrum at frequencies beyond LIGO's. Past milestones include the development of crucial subsystems for **LISA** and **LISA Pathfinder/ST7**, and JPL's major contributions to the **NANOGrav** program to detect nanoHertz GWs with pulsar-timing observations.

This Initiative was designed to ensure that JPL scientists and engineers remain **leaders in the new field of GW astronomy**, and specifically on the very-low-frequency band addressed by pulsar-timing arrays, and on the low-frequency band targeted by LISA.

This work positioned JPL to host the future LISA data-analysis center, and to lead the LISA ground segment in the US. It also helped JPL make a strong case for SMD/Astrophysics support of science with the DSN, and it identified and developed new talent for JPL technical and scientific programs.

FY18/19 Results:

In the **Bayesian analysis of noisy data**, we seek the posterior probability density of source parameters; this comes at significant computational cost since it requires the stochastic exploration of the likelihood surface at many locations in parameter space.
In Ref. [6], we show that one- or two-dimensional **marginalized Bayesian posteriors can be produced using deep neural networks** trained on large ensembles of signal + noise data streams.

Such networks (dubbed PERCIVAL, for *Posterior Estimation Results Computed Instantaneously Via Artificial Learning*) take as input a noisy signal, and **instantly output approximate posteriors**, represented either as a histogram or parametrically (e.g., as a Gaussian mixture). The loss function used in the training does not require that we compute the likelihood, but only that we provide the true source parameters.

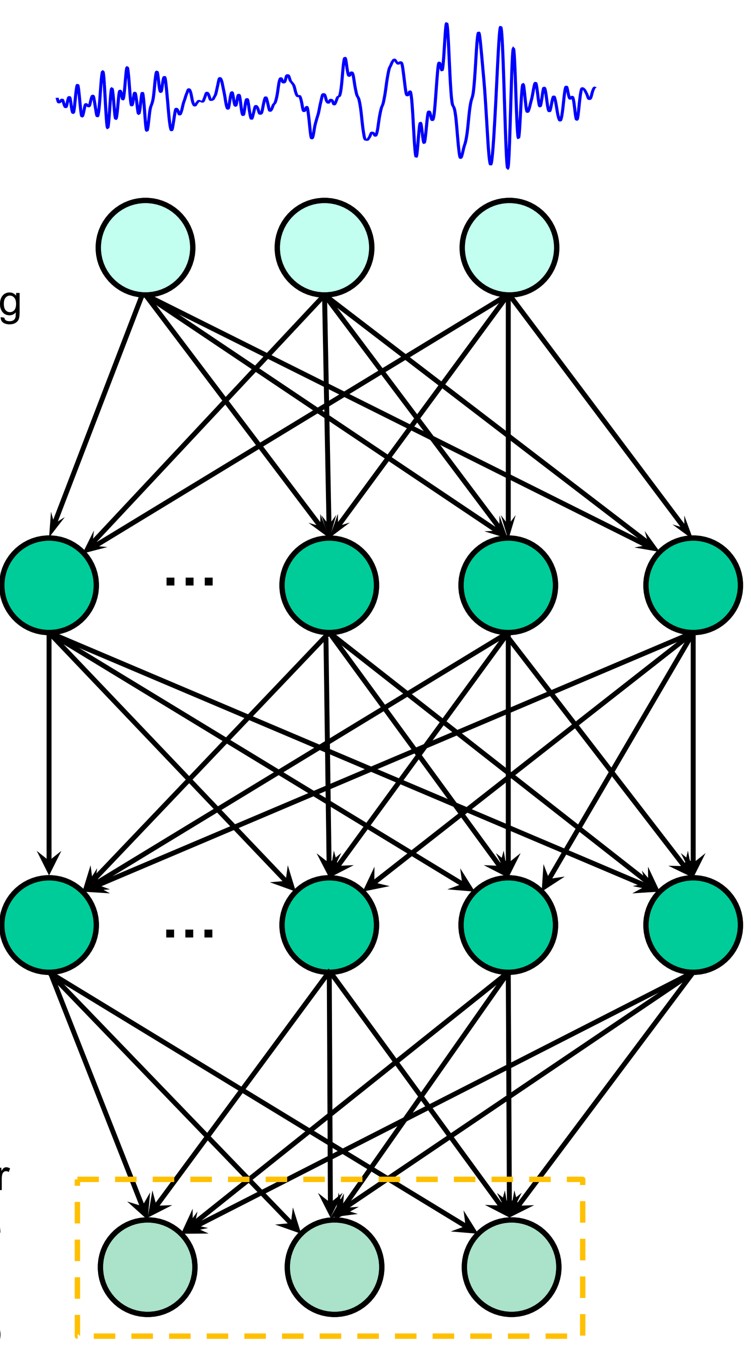
PERCIVAL's training is expedited by its forward counterpart ROMAN [5]—a neural network fitted to a waveform model in a reduced-order representation. ROMAN inputs source parameters and outputs the corresponding signal in milliseconds, at high accuracy; it provides a conceptually cleaner alternative to likelihood acceleration by surrogate waveforms and reduced-order quadrature.

Percival's prompt posteriors (for the appropriate waveform family) can be used for **binary coalescence alerts**, to generate **effective proposal kernels** for Monte Carlo methods, and for the **characterization of parameter-estimation prospects** for next-generation detectors such as LISA.

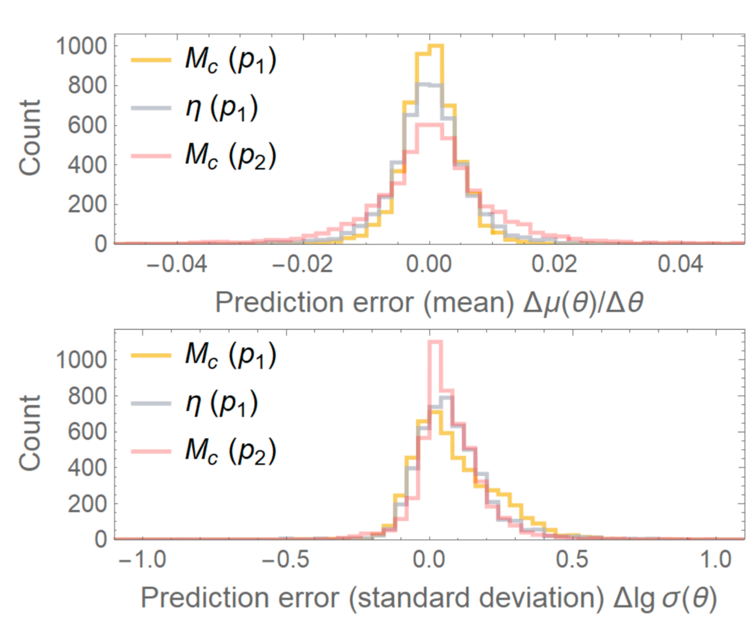
Input layer: reduced-order-modeling representation of signal + noise data

Hidden layers ···

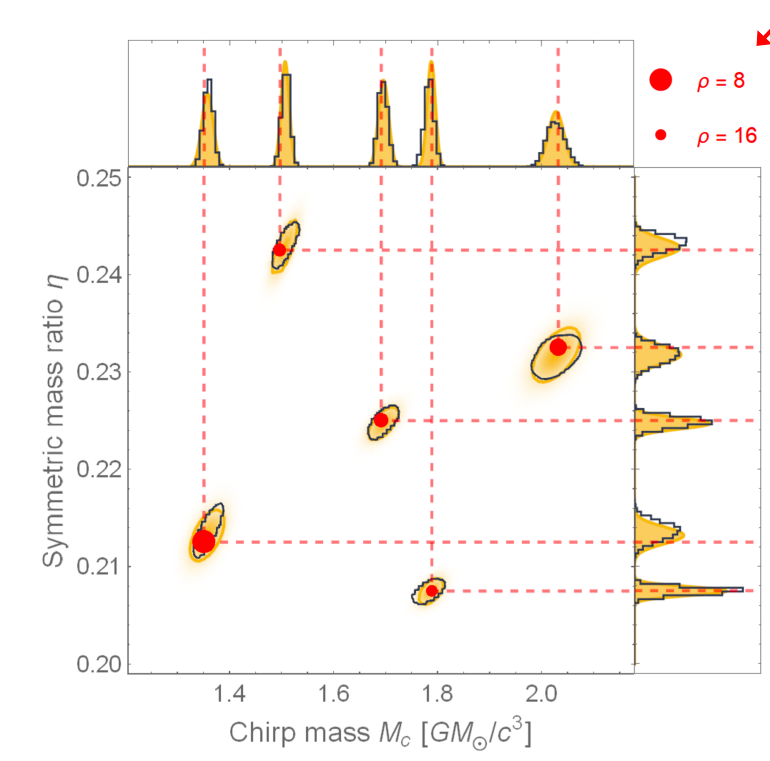
Cost function: in training, the posterior is evaluated at the **true parameters**, and the cost gradient is used to adjust network weights



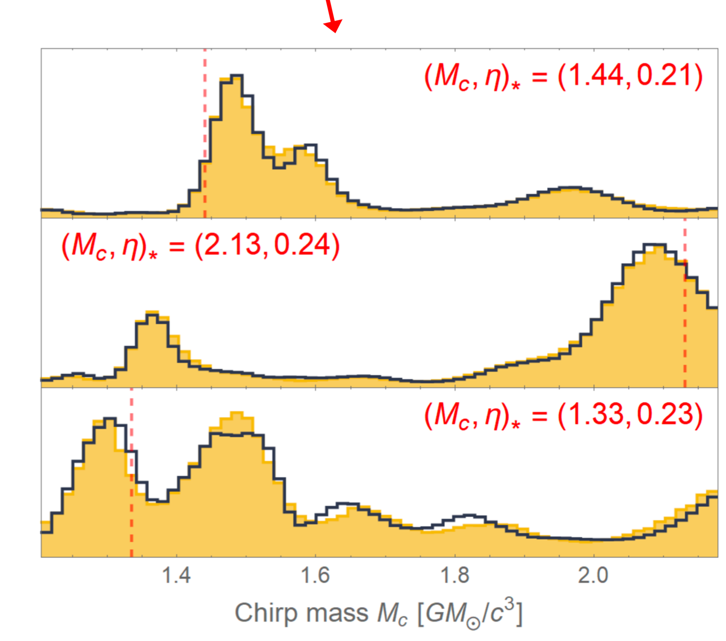
Output layer: Bayesian posterior represented as Gaussian mixture or histogram



Errors of network-estimated parameter means and standard deviations for 5,000 inspiral signals. (LISA-relevant component masses, orbital-momentum-aligned spins.)



Network-estimated and **true** chirp-mass/mass-ratio posteriors for five test moderate-SNR inspiral signals. (Multinormal posteriors.)



Network-estimated and **true** chirp-mass posteriors for three low-SNR inspiral signals. Note the recovery of multiple modes. (Histogram posteriors.)

Publications:

[1] NANOGrav collaboration, "The NANOGrav 11-Year Data Set: Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries," Astrophys. J. 880, 2 (2019). arXiv:1812.11585

[2] K. Islo, J. Simon, S. Burke-Spolaor, and X. Siemens, "Prospects for Memory Detection with Low-Frequency Gravitational Wave Detectors," submitted to Astrophys. J. (2019). arXiv:1906.11936

[3] S. Burke-Spolaor et al., "The Astrophysics of Nanohertz Gravitational Waves," Astronomy & Astrophysics Review 27 1 (2019). arXiv:1811.08826

[4] H. Wang, S. R. Taylor, M. Vallisneri, "Bayesian cross validation for gravitational-wave searches in pulsar-timing array data," MNRAS 487, 3644 (2019). arXiv:1904.05355

[5] A. J. K. Chua, C. R. Galley, & M. Vallisneri, "Reduced-order modeling with artificial neurons for gravitational-wave inference," Phys. Rev. Lett. 122, 211101 (2019). arXiv:1811.0549

[6] A. J. K. Chua & M. Vallisneri, "Learning Bayes' theorem with a neural network for gravitational-wave inference," Phys. Rev. Lett., in review (2019). arXiv:1909.05966

[7] A. J. K. Chua, "Sampling from manifold-restricted distributions using tangent bundle projections," Stat. Comput., in press (2019). arXiv:1811.05494

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